Fermi National Accelerator Laboratory

FERMILAB-Pub-92/180-A
June 1992

THE PHOTON/PROTON RATIO AS A DIAGNOSTIC TOOL FOR TOPOLOGICAL DEFECTS AS THE SOURCES OF EXTREMELY HIGH ENERGY COSMIC RAYS *

F.A. AHARONIAN[a], P. BHATTACHARJEE[a] AND D.N. SCHRAMM[a,b]

[a]The University of Chicago
5640 S. Ellis Avenue
Chicago, IL 60637

[b]NASA/Fermilab Astrophysics Center
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, IL 60510

Abstract

The hypothesis of topological defects (from Grand Unified and/or Planck scales) as the sources of extremely high energy ($> 10^{18}eV$) cosmic rays predicts unusually high content of gamma rays at energies $E \gtrsim 10^{20}eV(\gamma/p \geq 1)$ and $E \lesssim 10^{14}eV(\gamma/p \gtrsim 10^{-3})$. This can be used as a signature for testing the hypothesis in forthcoming experiments.

* Submitted to *Phys. Rev. Lett.*

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

The acceleration of the cosmic rays (CR), observed up to energies $E \gtrsim 10^{20} eV$[1], poses serious challange for any particle acceleration mechanism[2]. This has recently motivated some authors[3,4] to consider the possibility that CR particles above some energy may have a more "fundamental" origin in the sense that they may not have been accelerated at all; instead they may simply be the decay products of some sufficiently massive particles surviving from an early cosmological epoch. One possible realization of such a "non-acceleration" origin of CR is the process of collapse or annihilation of topological defects (TD)[3,4] such as magnetic monopoles, cosmic strings, domain walls, superconducting cosmic strings etc.[5], formed in a phase transition at some high energy scale such as the Grand Unification(GUT) scale or the Planck scale.

Because of their topological stability the defects can survive indefinitely; however, they can occasionally be destroyed due to collapse or annihilation, releasing the energy trapped in them in the form of massive quanta (hereafter referred to as X-particles) of the various fields (gauge bosons, higgs bosons, superheavy fermions) that 'constitute' the defects. The X-particles can then decay into quarks, gluons, leptons etc. The quarks and gluons would hadronize, that is produce, jets of hadrons. The latter would be mostly pions, together with a small fraction ($\sim 3\%$) of baryons (which finally end up as nucleons). The neutral pions decay producing gamma rays while the charged ones produce neutrinos. We thus obtain a natural mechanism of production of nucleons, gamma rays and neutrinos with energies up to $\sim m_X$, the mass of the X-particles. (For GUT energy scale defects, m_X can be as large as $O(10^{16}) GeV$). We shall refer to this topological defect-induced CR particle generation process as the "TD model" in order to distinguish it from the conventional acceleration scenarios ("A model").

The expected proton and neutrino spectra in the TD model have been calculated in Ref.[4]. In this *Letter* we present the expected γ-ray and proton spectra, and point out the unusually high content of γ-rays in CR ($\gamma/p \geq 1$) at the highest energies, predicted in the TD models. The details of our calculations will be presented elsewhere.

The diffuse extragalactic γ-rays in the A-model have a secondary origin. They are produced by the decay of π^0 mesons resulting from the interactions of CR protons with the microwave background radiation (MBR). In contrast, the γ-rays in the TD model are of "primary" origin in the sense that they are the direct by-products of the decay of the X-particles ($X \to q \to \pi^0 \to \gamma$). Moreover, the π^0 mesons along with the charged pions are the dominant products of the X-particle decays, the production ratio of π^0/p being $\zeta \approx \frac{1}{3}\left(\frac{0.97}{0.03}\right) \approx 10$ assuming $\sim 3\%$ nucleon content of the hadronic by-products of each X-particle. In addition, of course, there are γ-rays of secondary origin due to interactions of the protons (produced by the decays of X-particles) with the MBR; but the contribution of this channel is much less.

Throughout our discussions, we will be interested in energies $E \geq 10^{19} eV$, which allows us to ignore possible cosmological evolutionary effects associated with both the CR sources and the MBR, since at these energies the path lengths of protons as well as photons in the intergalactic medium (IGM) are much less than the horizon (Hubble scale) of the universe. Here we assume that the process of particle production occurs uniformly throughout the universe. The production spectrum of protons in the A-model generally has a power-law behavior: $q_p(E) = q_0 E^{-\alpha}$. In the TD model the production spectrum is determined by the physics of quark fragmentation into hadrons. The resulting production spectrum in the TD model can also be approximated[5,3] by power-laws with $\alpha \simeq 1.32$ in the energy range $10^{-10} m_X/2 \leq E \leq 10^{-2} m_X/2$, and $\alpha \simeq 1.95$ for $10^{-2} m_X/2 < E \leq 0.32 mx/2$[4].

The equilibrium spectrum of protons, I_p, may be obtained in the continuous energy loss (CEL) approximation[6]: $I_p(E) = \frac{q_0 E^{-\alpha}}{4\pi(\alpha-1)} \lambda_p(E)$, where $\lambda_p(E) \equiv Ec/\left(dE/dt\right)_p$ is the mean attenuation length of protons due to interactions with MBR as well as due to expansion of the universe. At $10^{19} eV \leq E \leq 3 \times 10^{19} eV$ and $E \geq 3 \times 10^{20} eV$ the energy-loss rate, determined mainly by the processes of e^+e^- pair production and photomeson production, respectively, is proportional to E ($\lambda_p \sim const.$)[7]. Therefore, the equilibrium spectrum in these energy ranges repeates the shape of the production spectrum: $I_p(E) \propto E^{-\alpha}$.

The deviation from the shape of the production spectrum occurs between $3 \times 10^{19} eV$ and $3 \times 10^{20} eV$. The energy, $E_{1/2}$, of the "black-body cutoff"[8] of the proton spectrum is $\sim 5 \times 10^{19} eV$. For those models, the maximum occurring at $E \sim 4 \times 10^{19} eV$ (see Fig. 1) has nothing to do with the recoil proton "bump" (which, however, is a feature of the spectrum of a single point source[9]) or a discontinuous distribution of such sources, but is simply the result of the positive index of the function $E^3 I(E) \propto E^{3-\alpha}$ (for $\alpha < 3$) at $E \leq E_{1/2}$.

The equilibrium proton spectra calculated for the TD model, $p(TD)$, as well as for the A-model, $p(A2)$ and $p(A3)$ (for $\alpha = 2$ and $\alpha = 3$, respectively), are shown in Fig. 1. The spectra $p(A2)$ and $p(TD)$ are normalized to the experimental fluxes at $E \sim 4 \times 10^{19} eV$, where there is relatively good agreement between Fly's Eye and Haverah Park data.

The hard production spectrum ($\alpha = 1.32$ for the TD-model and $\alpha = 2$ for the A-model) may, in principle, explain an absence of a noticeable cutoff in the measured flux above $5 \times 10^{19} eV$[10]. At the same time the hard production spectra are unable to explain the CR fluxes measured at $E \leq 10^{19} eV$, even under extreme assumptions concerning cosmological evolutionary effects. Therefore, for the lower energy part of the spectrum we need to assume an additional soft (galactic?) component of CR. The CR spectrum at $E \leq 10^{19} eV$ may, in principle, be explained also by an extragalactic component of CR with $\alpha = 3$; however, in this case the spectrum is in conflict with the reported CR fluxes above $5 \times 10^{19} eV$ (see Fig. 1), although this might be remedied with a discontinuous distribution of sources[9].

A general feature of the TD model is the unusually flat behavior of the proton production spectrum. The power-law index of the hardest spectrum provided by any reasonable acceleration mechanism (e.g., by shock waves) is $\alpha \sim 2$. Therefore, the spectral measurements of CR above $E_{1/2}$ in forthcoming experiments would, in principle, provide a choice between the TD- and A models. As seen from Fig. 1, at a given normalization the difference between $p(TD)$ and $p(A2)$ becomes noticeable at $E < 10^{19} eV$ and again at $E > 10^{20} eV$.

At $E < 10^{19} eV$ discrimination between these models is problematic due to the presence of the stronger component of the observed CR, and so the analysis of the proton spectrum at $E \geq 10^{20} eV$ seems preferable. However, as we argue in the following, a more reliable and unambiguous parameter for recognition of the origin of the highest energy cosmic rays is the γ/p ratio near and above $E_{1/2}$.

The γ-ray production spectrum in the TD model can be obtained from the pion production spectrum as $q_\gamma(E) = 2\int_E^\infty dE' E'^{-1} q_{\pi^0}(E')$, where $q_{\pi^0}(E) = \zeta q_p(E)$, and $\zeta \simeq 10$ is the π^0/p ratio in the decay of X-particles. The γ-rays as well as electrons and positrons (from the charged pion decays) initiate electromagnetic cascades in the photon fields of the MBR and the universal radio background (URB). In general, it is necessary to consider the integro-differential kinetic equations for the cascade development because of the catastrophic nature of both e^+e^-pair production and Compton processes that give rise to the cascade. Nevertheless, in the extreme Klein-Nishina regime the cross sections of these processes become similar, which reduces the cascade problem to the much simpler *single* high-energy "particle" transfer problem[11]. This "particle", that spends its lifetime in two states ("electron" and "photon"), is hereafter called a "e/γ" particle. Due to the strongly catastrophic nature of the elementary processes, when one of the secondaries (e or γ) carries the main part of the primary energy, the energy loss of the "e/γ" particle is essentially gradual. Thus the equilibrium spectrum of cascade γ-rays may be obtained in the continuous energy-loss approximation [12]:

$$I_\gamma(E) = \frac{\zeta(1+\kappa)}{2\pi\alpha(\alpha-1)} q_0 E^{-\alpha} \lambda_\gamma^{cas}(E), \qquad (1)$$

where the parameter κ takes into account the contribution from $e^{\pm}$ (from the charged pion decays) to the cascade development; $k \simeq 0.85$ for $\alpha = 1.32$. In Eq. (1) $\lambda_\gamma^{cas}(E)$ is the mean attenuation length of the cascade γ-rays, which has been calculated in Ref. [13] for different assumptions concerning the URB and the intergalactic magnetic field (IMF). In calculating $\lambda_\gamma^{cas}(E)$ the following processes were considered: (i) single- and double pair production at γ - γ interactions and Compton scattering of the electrons in the fields of MBR and URB, (ii) synchrotron cooling of the cascade electrons, and (iii) the triplet pair production (TPP) ($e + MBR \rightarrow e^+e^-e'$). The TPP, which may be considered as a gradual energy-loss process for the cascade electrons, has recently been realized[13] to be an important process in astrophysical objects. For instance, this process reduces the path length of the cascade γ-rays at $E = 10^{20} eV$ by more than a factor of five[12].

The path length of cascade γ-rays strongly depends on the density w_{URB} of URB and on the strength B of the IMF. Unfortunately, both these parameters continue to be highly uncertain. The present estimate of B based on the Faraday rotation measurements, is as low as $3 \times 10^{-11} G$ [14], though much higher values of B, especially in the Local Supercluster, cannot be excluded. Besides, it is known that attribution of the measured density of the isotropic radio flux ($w_R \sim 10^{-7} eV\ cm^{-3}$) to the URB faces certain problems (see e.g., [15]). For $B \leq 10^{-12} G$ and $w_{URB} \ll w_R$, the mean attenuation length of cascade particles at $E \geq 10^{20} eV$ becomes more than the attenuation length of protons, and therefore, in this energy domain the ratio of $\gamma/p \sim q_\gamma \lambda_\gamma / q_p \lambda_p \gtrsim 10$. A more realistic assumption on the value of w_{URB}, e.g., $w_{URB} \approx w_R$ leads to a reduction of the attenuation length of cascade particles by a factor of as much as 5. Moreover, even at relatively low values of magnetic field, $B \sim 10^{-10} G$, the cascade development at $E \geq 10^{20} eV$ due to synchrotron cooling of electrons becomes inefficient and the γ-ray flux is determined mainly by the "direct" (i.e., not interacting with the ambient photon gas) γ-rays.

The equilibrium γ-ray spectra calculated for different values of B and w_{URB} are shown in Fig. 1. It is seen that even for extreme values of B and w_{URB}, namely, $B \gg 10^{-10} G$, and $w_{URB} = w_R$, the ratio of γ/p at $E \geq 10^{20} eV$ due to "direct" γ-rays should exceed unity in the TD model. The flux of "direct" γ-rays has some uncertainty (by a factor of $\sim$ 2) connected with the value of the cutoff frequency in the spectrum of the measured radio background; however, this uncertainty cannot influence the general conclusion concerning a high γ/p ratio at the highest energies. As seen from Fig. 2, even for the extreme (and rather unrealistic) assumptions, namely, $B \ll 10^{-12} G$ and $w_{URB} \ll w_R$, which give the most optimistic estimates, the γ/p ratio in the A-model (curves 5 and 6) remains below the level of γ/p ratio expected in the TD-model for the opposite extreme assumptions, namely, $w_{URB} = w_R$, and $B \gg 10^{-10}G$, which give the most pessimistic estimates (curve 1). So the curve 1 in Fig. 2 can be considered as a boundary between TD- and A- "domains". The remarkable features[16] of air showers initiated by primary γ-rays at $E \geq 10^{20}eV$ allow us to hope that this boundary will be probed by the forthcoming powerful detectors, in particular, by the High Resolution Fly's Eye[17], or the proposed $5000km^2$ giant air shower array[18]. These experiments can provide unambiguous arguments for or against the proposed TD-model. Moreover, in the case of realization of the TD model, it may be possible to probe the intergalactic magnetic field in the 10^{-12}— $10^{-10}G$ domain by measuring the γ/p ratio between $\sim 5 \times 10^{19}$—$5 \times 10^{20}eV$ (compare curves 1, 2 and 3 in Fig. 2).

Valuable information about the origin and propagation of extragalactic CR is expected to be contained also in the γ-ray fluxes at $E \lesssim 100TeV$[19]. The spectrum of γ-rays in this energy interval is determined mainly by the properties of cascade development in the MBR, and hence has a standard shape which may be approximated as $I(E) \propto E^{-1.5}$ for $E \lesssim 10TeV$, and $I(E) \propto E^{-1.75}$ for $E > 10TeV$ with a sharp cutoff above $E \sim 100TeV$[20]. The absolute flux of these γ-rays is determined by the total energy of the electromagnetic radiation above $100TeV$ initiating the cascade in the MBR. For the A-model, the flux of these γ-rays is expected only at a level $\lesssim 10^{-5}$ of the CR background, which makes the detection of this component of γ-rays by modern air shower detectors rather problematic. However, in the TD-model, due to the high production rate of γ-rays and electrons, the integral γ-ray fluxes at $E \leq 100TeV$ are expected at the level of 10^{-3}—10^{-2} of the CR (see Fig. 3). Detection of this component is in principle possible (though very difficult) by powerful γ-ray detectors like CASA, HEGRA, CYGNUS, etc. It should be noted that the γ-ray fluxes in this energy range depend weakly on the value of the magnetic field, they are sensitive to m_X. So it may be possible to probe m_X by measuring the γ/p ratio at energies $E \leq 100TeV$.

To summarize, we are noting that GUT processes may be observed through the use of γ/p ratio in extremely high energy cosmic rays.

Acknowledgements: The authors would like to thank J. W. Cronin and C. Hill for discussions. This work was supported in parts by NSF, DoE and NASA grants at the University of Chicago, and by the DoE and by NASA through grant NAGW 2381 at Fermilab.

References

[1] M. Nagano and F. Takahara (editors), ***Astrophysical Aspects of the Most Energetic Cosmic Rays*** (World Scientific, Singapore, 1991).

[2] See, for example, W. H. Sorrell, in Ref. [1], p. 329—334.

[3] C. T. Hill, Nucl. Phys. **B224**, 469 (1983); C. T. Hill, D. N. Schramm and T. P. Walker, Phys. Rev. **D36**, 1007 (1987); P. Bhattacharjee and N. C. Rana, Phys. Lett. **B246**, 365 (1990).

[4] P. Bhattacharjee, in Ref. [1], p. 382–399; P. Bhattacharjee, C. T. Hill and D. N. Schramm, Fermilab Preprint FERMILAB-Pub-91/304-A (October 1991).

[5] T. W. B. Kibble, J. Phys. **A9**, 1387 (1976); A. Vilenkin, Phys. Rep. **121**, 263 (1985).

[6] The CEL approximation in case of single-point-source spectrum leads to essential errors due to strong dependence of the interaction probability on the energy of protons. Nevertheless, in case of universal equilibrium spectrum the peculiarities (like "bump") disappear, and the CEL approximation becomes acceptable; see, F. A. Aharonian, B. L. Kanevsky and V. V. Vardanian, Ap. Sp. Sc. **167**, 93 (1990).

[7] F. W. Stecker, Phys. Rev. Lett. **21**, 1016 (1968); G. Blumenthal, Phys. Rev. **D1**, 1596 (1970); V. S. Berezinsky and S. I. Grigor'eva, Astron. Astrophys. **199**, 1 (1988).

[8] K. Greisen, Phys.Rev.Lett. **16**, 748 (1966); G. T. Zatsepin and V. A. Kuz'min, JETP Lett. **4**, 78 (1966).

[9] C. T. Hill and D. N. Schramm, Phys. Rev. **D31**, 564 (1985).

[10] See, for example, A. A. Watson in Ref. [1], p 2–19.

[11] F. W. Stecker, Ap. Sp. Sc. **20**, 47 (1973); R. J. Gould and Y. Rephaeli, Ap. J. **225**,318 (1978).

[12] F. A. Aharonian, to be published (1992).

[13] A. Mastiachiadis, MNRAS **253**, 235 (1991); C. D. Dermer and R. Schlickeiser, Astron. Astrophys. **252**, 414 (1991).

[14] E. Asseo and H. Sol, Phys. Rep. **48**, 309 (1987).

[15] M. S. Longair and R. Sunyaev, Sov. Usp. Fiz. Nauk. **105**, 41 (1971).

[16] F. A. Aharonian, B. L. Kanevsky and V. A. Sahakian, J. Phys. G: Nucl. Phys. **17**, 1909 (1991)

[17] See, for example, E. C. Loh (for HiRes collaboration) in Ref. [1], p.345—353.

[18] J. Cronin, private communication.

[19] J. Wdowczyk and A. W. Wolfendale, Ap. J. **349**, 35 (1990); F. Halzen, R. J. Protheroe, T. Stanev and H. P. Vankov, Phys. Rev. **D41**, 342 (1990).

[20] F. A. Aharonian and A. M. Atoyan, Sov. Phys. JETP. **62**, 189 (1985); R. J. Protheroe, MNRAS **221**, 769 (1986).

Figure Captions:

Fig. 1. Equilibrium spectra of protons and gamma-rays. The curves $p(A2)$ and $p(A3)$ are the proton spectra in the A-model with $\alpha = 2$ and 3, respectively. The curve marked $p(TD)$ is the proton spectrum in the TD-model. The curves 1, 2, 3, 4 are equilibrium γ-ray spectra calculated for TD model: (1) Direct γ-rays; (2) cascade γ-rays neglecting interactions with the intergalactic magnetic field ($B \ll 10^{-12}G$) and universal radio background ($w_{URB} \ll w_R$); (3) cascade γ-rays with $w_{URB} = w_R$, $B = 3 \times 10^{-11}G$; (4) same as (3) with $B = 10^{-10}G$.

Fig. 2. The γ/p ratio expected in the TD- and A-models. The curves marked 1, 2, 3 and 4 are for the TD model. The curves 5 and 6 are for the A-model with $\alpha = 2$ and 3, respectively. (1) Direct γ-rays; (2) cascade γ-rays with $w_{URB} = w_R$ and $B = 10^{-10}G$; (3) Same as (2) except $B = 3 \times 10^{-11}G$. The curves 4, 5 and 6 are for $w_{URB} \ll w_R$ and $B < 10^{-12}G$.

Fig. 3. The expected γ-ray fluxes below $100TeV$ for the TD model. The value of m_X is as indicated near the curves. The solid curves are for $B = 0$ and the dashed curves are for $B = 10^{-10}G$. The integral CR flux is also shown for comparison.

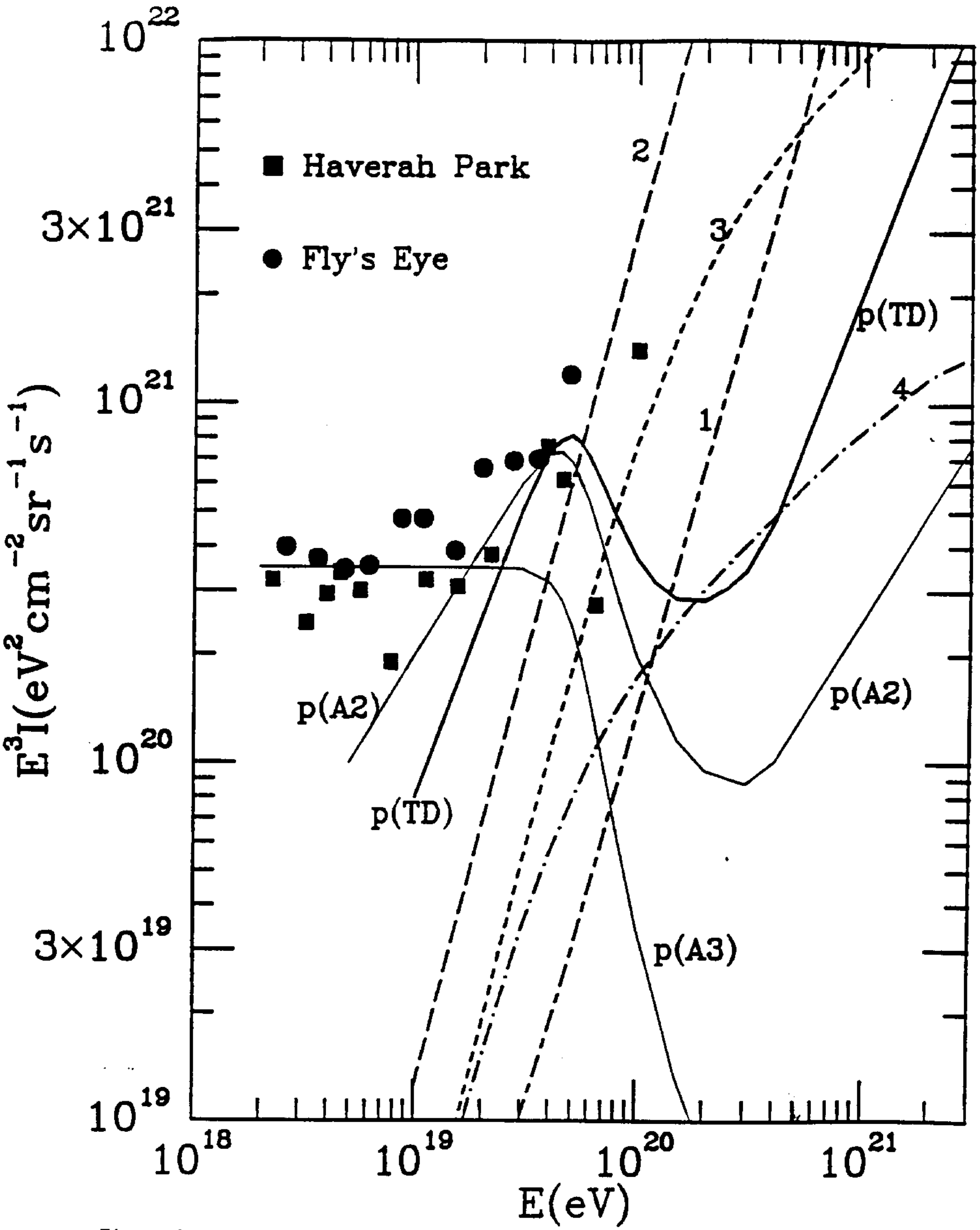
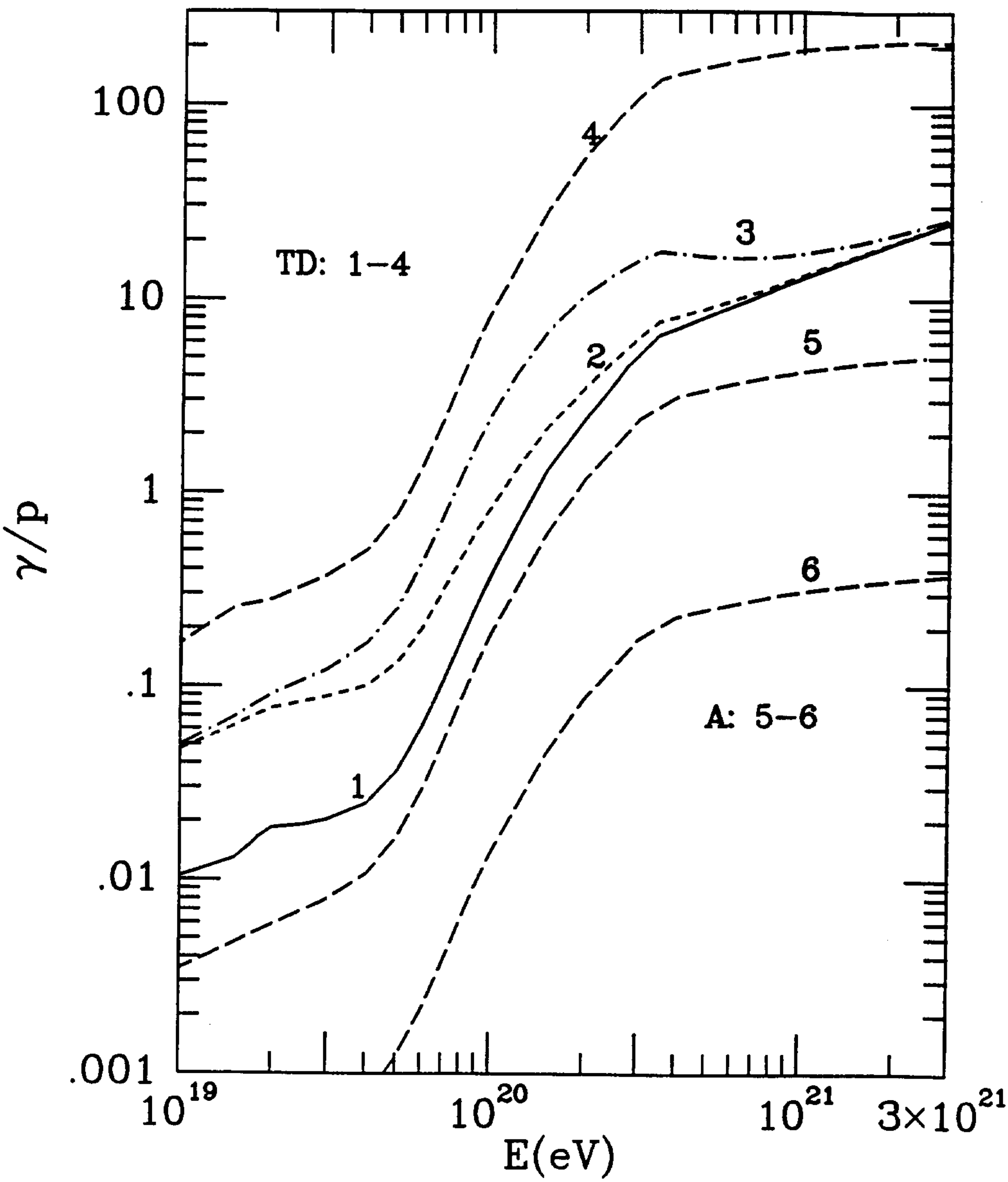
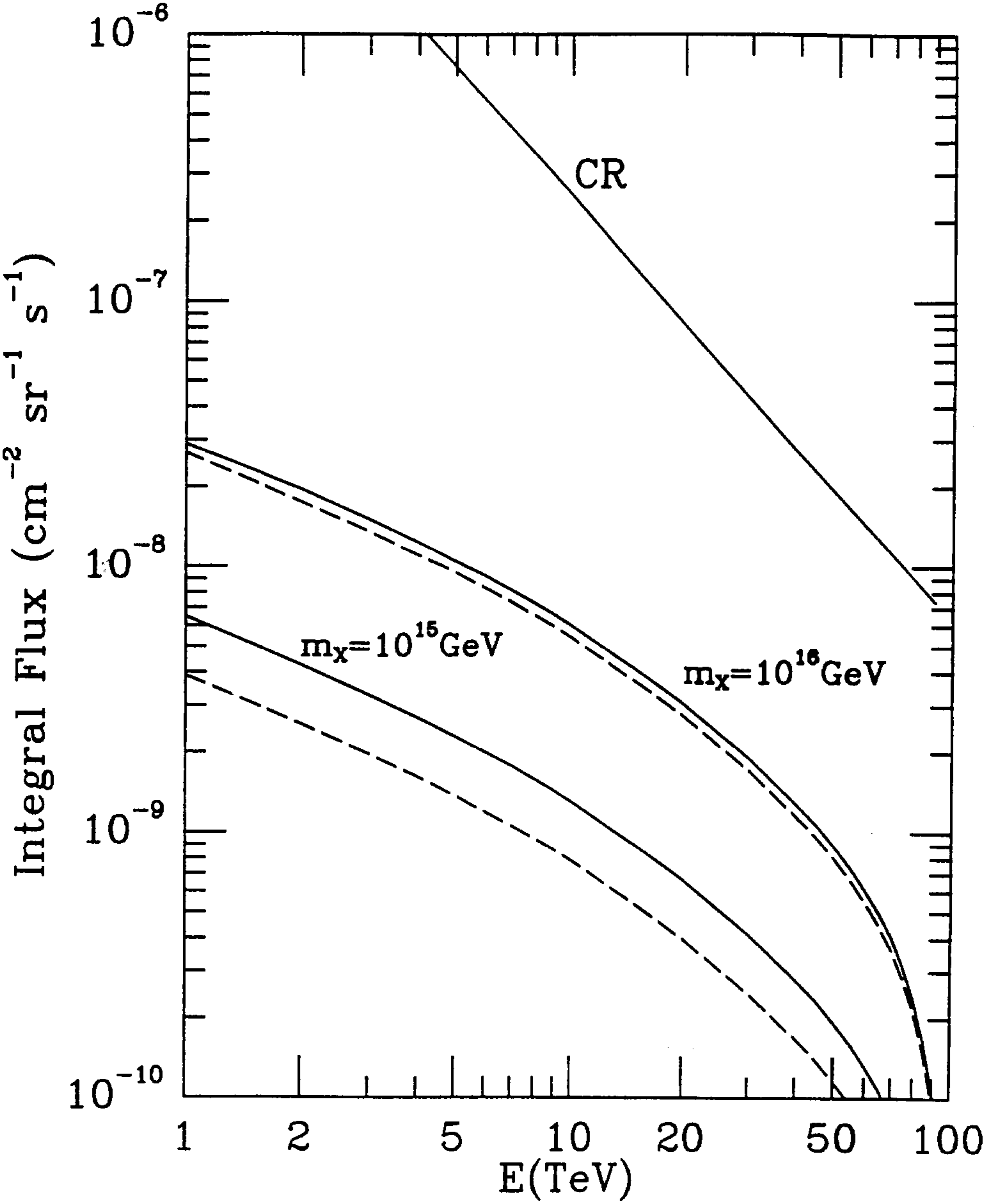

10^{22}
3×10^{21}
10^{21}
10^{20}
3×10^{19}
10^{19}
$E^3 I(eV^2 cm^{-2} sr^{-1} s^{-1})$
Haverah Park
Fly's Eye
2
3
1
4
p(TD)
p(A2)
p(TD)
p(A2)
p(A3)
10^{18}
10^{19}
10^{20}
10^{21}
E(eV)

Figure 1



100
10
1
.1
.01
.001
γ/p
TD: 1-4
A: 5-6
1
2
3
4
5
6
10^{19}
10^{20}
10^{21}
3×10^{21}
E(eV)

Figure 2



Integral Flux (cm^{-2} sr^{-1} s^{-1})
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
CR
$m_X=10^{15}$GeV
$m_X=10^{16}$GeV
1
2
5
10
20
50
100
E(TeV)

Figure 3